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PRINCETON UNIVERSITY

DEPARTMENT OF AERONAUTICAL ENGINEERING

Office of Naval Research, Department of the Navy

and

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Periodic Status Report
October 15, 1952 - April 15, 1953

"Viscous Effects in Supersonic Flow"

Contract No. N6-onr-270, Task Order No. 6,
Project No. NR-061-049

4" x 8" Tunnel

Base Pressure and Allied Studies

Studies of the flow around the base of an ogive cylinder body with a length to diameter ratio equal to 8 at Mach number 3 have been completed for the case of completely turbulent flow. A report is now in progress reporting these results. These tests, which covered a Reynolds number range from about 5 million to 50 million, were primarily designed as a detailed flow study of the region behind the base in an attempt to construct the complete flow field for the case where the boundary layer leaving the body was turbulent. The most interesting result of this study has been the examination of static pressures on the axis behind the body. It was expected that the pressure would increase from the low base pressure value to the free stream value in some smooth fashion. The experimental results show that (1), there is an over-compression, sometimes as high as 100% occuring approximately four diameters downstream of the body and (2), then a slow expansion of the wake back to ambient conditions. Free stream static pressures are not approached on the axis for distances less than about 10 diameters. These results have been explained on the basis that the compression caused by the conical flow behind the base and the trailing shock structure (the only mechanism to turn the flow back to the axial direction) gives a considerably higher pressure ratio than the two dimensional expansion at the corner of the base. As a result, pressure at the axis is considerably higher than ambient pressure and an expansion wave system must be generated to bring this pressure down to ambient. A re-examination of the theory shows that such effects can also be predicted but further results are necessary before verification can be made. A test program to examine this detailed base flow is being set up for conditions which will have laminar and transitional conditions of the boundary layer at the base.

In an attempt to get the effect of the flow leaving a body of revolution at an angle to the axis, tests have been started on series of [illegible] cones of various conical angles. Although the geometrical length of these cones varies (the base diameter is held constant) the variable Reynolds number characteristic of the tunnel allows examination of the flows for the same Reynolds numbers for all bodies over a range of Reynolds numbers. The effect of flow deflection angle must be included in the Crocco-Lees theory if it is to predict base pressures on bodies which have surfaces at the base not parallel to the axis. This program has been combined with a series of tests of the same cones as above with the addition of various length cylindrical afterbodies. These tests are designed to study the effect of the corner formed by the junction of the cone and cylinder on the boundary layer and the subsequent variations in base pressure. Preliminary tests have been carried out on both of these programs and the present test program includes considerable work on this phase.

Shock Wave Boundary Layer Interaction Studies

As part of the over-all program in the study of shock waves and boundary layers and their interactions, a series of tests to examine the details of a shock wave boundary layer interaction have been studied in the big tunnel where the pressure rise has been caused by a corner. This method provides a phenomena in which the complication of the initial or incident shock is eliminated and the compression is determined by the wall shape. Previous tests have been made in sharp corners varying with flow deflections from 5° to 25° at a Mach number of 3. A series of tests were started on corners formed by various radii to examine the effect of spreading out the pressure rise and allowing centrifugal forces to play a greater part in the interaction. Results have been obtained for several low angle compressions but blockage difficulities have forced suspension of the test program for the present. Modifications to the diffuser block should relieve this difficulty and allow completion of the test program. Preliminary results already show a very considerable difference in the sharp and smooth corner studies with the curved walls (centrigual effects very important) supporting much higher pressure ratios have been obtained in the sharp corner tests. This work is of particular importance in such applications as ram jet inlets and supersonic compressors.

2½" x 2" Tunnel

A series of tests have been made on the interaction between an oblique shock wave and the turbulent boundary layer on the nozzle wall of the 2½ x 2" tunnel at Mach number = 3. Shock wave strengths from 0 to 15° have been examined. The boundary layer has been held constant and is fully turbulent (a Reynolds numbered based on displacement thickness of about 7000). For shock wave strengths below 6°, studies of the two dimensionality of the flow shows that quite severe cross flows are experienced even though the shock generating wedge completely spans the tunnel. All attempts to get two dimensional flows have been unsuccessful although static pressures measured on centerline are consistent. As a result of this investigation no data has been presented for these low angles and considerable doubt as to the veracity of other published data now exists. The literature mentions no examination of the two dimensional condition. The pressure distributions on centerline show a peak in the pressure rise curve with the final pressure being considerably less than the theoretical predicted value. This is in agreement with other published results but appears to be due in large part to the three dimensional nature of the flow. For these weak shock strengths, small variations in the flow and boundary layer characteristics must play as important a part in the phenomena as the weak shock strengths tested.

Above 6°, two dimensional characteristics could be obtained and a summary of the results for shock wave strengths of 7 to 15° are shown in the following chart. The boundary layer thickness is indicated on the horizontal scale as δ and it can be seen that this interaction spreads out only to 10 to 15 boundary layer thicknesses in constrast with the laminar case which may extend 50 or more boundary layer thicknesses upstream. The development of the pressure rise on the wall with varying strength shocks has some of the characteristics of the laminar boundary layer interaction. In particular, an inflection in the pressure rise curve is found

which has not been obtained by previous investigation because of the relatively low shock strength used.

In the study of this phenomena some considerable effort has been put into the development of colored Schlieren photographs. Colored Schlieren photography is not new, but its value has been primarily in the field of publicity. Past techniques have necessitated long exposures and therefore it has not proved an important research tool. A technique has been developed at this laboratory for taking colored Schlieren photgraphs with a microsecond flash. The color system consists of a special confined light sources, a prism, the conventional Schlieren optics, and the use of a slit instead of the conventional knife edge. Ektachrome film and special processing developed in our photographic lab are used to obtain a 2" x 2" transparency. In these Schlieren photgraphs, each pressure gradient is identified by a particular color. As a result, the final photgraph shows considerably more detail than the ordinary Schlieren because of the eye's sensitivity to color. For example, a small compression and a small expansion, side by side, will be two completely different colors in the colored Schlieren system whereas they would be only slighly different in the gray scale for ordinary Schlieren photographs. An examination of such photographs has given some considerable information on the structure of the shock wave boundary layer interaction heretofor not available. Below a shock strength of 8° the reflection of the shock wave from the turbulent layer is a "regular" reflection, i.e., the incident shock wave is reflected as a single compression wave. At about 8°, a change takes place, the influence of the incident shock wave extends upstream and the reflection consists of initial compression, a small expansion fan and a second compression. As the incident shock strength becomes stronger this phenomena spreads out and becomes a well defined initial reflected shock followed by a separated region. The incident shock reflects from the top of this region as a strong expansion and the attendant reattachment and turning of the separated layer cause the second compression. The change in reflection characteristics, as determined from the color Schlieren photographs, agrees with the occurence of the inflection point in the wall static pressures (see the figure for shock wave strength of 9°). Total head surveys are now being undertaken through the interaction region to determine the size and characteristics of the separated region and other flow characteristics.

Theoretical Work

The obtaining of detailed experimental results on the shock wave boundary layer interaction has stimulated additional work along theoretical lines on the prediction of the shock wave boundary layer interaction effects. The Crocco-Lees theory seems to be able to give a very good representation of the flow with the exception of the sharp pressure rise due to the initial reflected shock. It will perhaps not be possible at the present time to predict this theoretically. The results of the detailed total and static surveys have at least provided a good model and attempts are now being made to predict this initial pressure rise from purely theoretical considerations. There seems to be some indication that this initial pressure rise, i.e., the pressure rise before the inflection point, may be very little influenced by Mach number and if so, provides a critical parameter in any solution.

The Crocco-Lees application to base pressure was re-examined in an attempt to predict the over-shoot of the pressure on the axis behind the base. The method of calculation made it necessary to contruct the external inviscid flow which must be done by a three-dimensional method of characteristics. Some preliminary work along this line has shown pressures on the axis which rise above the ambient static pressure but the complications of the external flow calculations makes it impractical to push this solution further. This work will be continued as more experimental results are available in this separated region behind the base.

Reports in Progress

1) A rough draft of a report on the results of the detailed study of the flow behind blunt based body of revolution with a turbulent boundary layer has been completed. A compilation of the results has shown the need for a few more test points which should be obtained within the next month or so. The report will be ready for publication shortly thereafter.

2) A report presenting the results of the work on the interaction between various strength shock waves and a turbulent boundary layer is also in rough draft form. This report should also be forthcoming within the next month to six weeks.

3) A summary of the results on the shock wave boundary layer interaction studies has been prepared for presentation at the ASME Heat Transfer Meeting in California the end of June. The paper will be published in the proceedings of this meeting.

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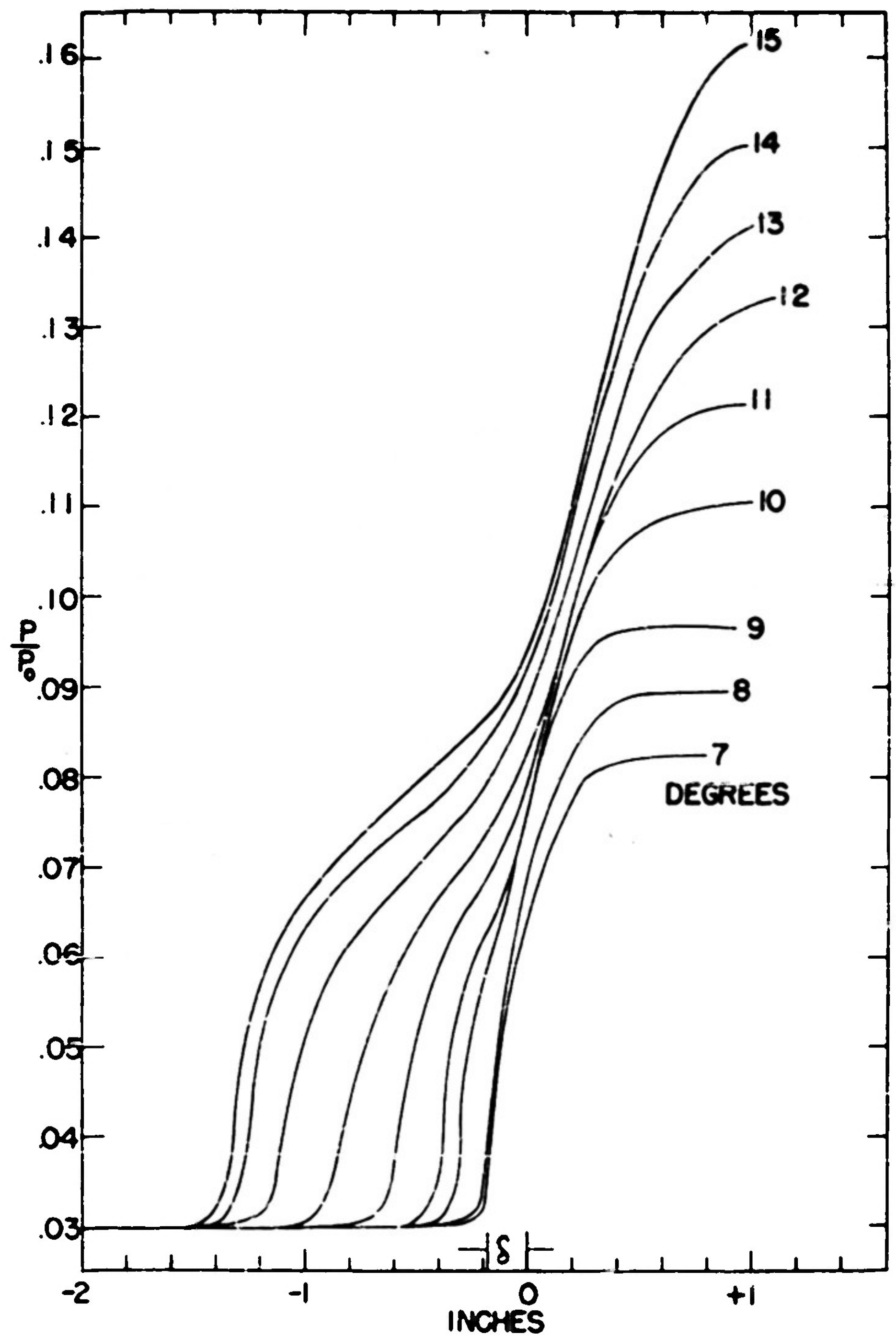

Summary of Wall Static Pressures for Various Strength Shocks. M = 3.0